

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

X-660-71-243  
PREPRINT

NASA TM X- 65590

# COSMIC-RAY EFFECTS IN THE GUM NEBULA

R. RAMATY  
E. A. BOLDT



JUNE 1971

**GSFC**

**GODDARD SPACE FLIGHT CENTER**

**GREENBELT, MARYLAND**

**N71-28567**

FACILITY FORM 602

(ACCESSION NUMBER)

18

(PAGES)

TMX-65590

(NASA CR OR TMX OR AD NUMBER)

(THRU)

G3

(CODE)

29

(CATEGORY)

## COSMIC-RAY EFFECTS IN THE GUM NEBULA

R. Ramaty and E. A. Boldt  
NASA-Goddard Space Flight Center  
Greenbelt, Maryland 20771

Abstract We investigate the effects of low energy heavy nuclei from the supernova explosion on nearby interstellar space. In addition to the ionization and heating of the Gum Nebula, these particles may produce detectable fluxes of X-rays and gamma rays, both as continuum radiation and line emission.

Paper presented by R. Ramaty at the Symposium on The Gum Nebula and Related Problems, Goddard Space Flight Center, Greenbelt, Maryland, May 19, 1971. To appear in The Gum Nebula and Related Problems, edited by S. P. Maran, J. C. Brandt and T. P. Stecher.

## INTRODUCTION

The possibility that the ionization of the Gum Nebula may have been produced by energetic charged particles from the supernova Vela X has been suggested by Ramaty et al. (1971). The principal features of this model are the existence of a prolonged source of ionization and heating and the possibility of direct detection of hard photon emissions from contemporary fluxes of energetic particles in the nebula. In the present paper, we shall summarize the model and discuss its main features. We shall also present an estimate of gamma-ray line emission from the interaction of energetic nuclei with the ambient gas and we shall discuss some additional ideas regarding the maintenance of a possible high temperature in the filaments of the nebula.

### Particle Propagation and Energy Deposition

A necessary requirement of a cosmic-ray model of the Gum Nebula is that in a time less than or equal to the age of the supernova remnant the particles should be capable of both reaching the outer edges of the nebula and depositing a significant fraction of their energy as ionization loss to the ambient gas.

A lower limit on the velocity  $c\beta$  of the ionizing nuclei can be obtained by assuming rectilinear propagation of particles in the nebula, i.e.

$$\beta > L/ct \quad (1)$$

where  $L$  and  $t$  are the nebular radius and age respectively. If we adopt an age of about  $10^4$  years, as deduced from the period and rate of change of period of PSR 0833 (Reichley, Downs and Morris, 1970), and a nebular

radius of about 360 pc, as obtained (Alexander et al., 1971) from Ly $\alpha$  absorption data and a local hydrogen density of  $0.24 \text{ cm}^{-3}$ , the lower limit on  $\beta$  is about 0.1 corresponding to an energy per nucleon  $\epsilon \gtrsim 5 \text{ MeV/nucleon}$ . It should be remembered that this lower limit is subject to considerable uncertainties in both  $t$  and  $L$ . In particular, if the age is larger than  $10^4$  years (Shklovsky, 1970), the Gum Nebula may have been produced by even lower energy particles.

Cosmic-ray particles in general do not propagate along rectilinear paths but follow magnetic field lines and are scattered by irregularities in the field. The mean distance traversed in such diffusive motion may be approximated by

$$L \approx (2\lambda c\beta t)^{1/2} \quad (2)$$

where  $\lambda$  is the diffusion mean free path. For  $L \approx 360 \text{ pc}$  and  $t \approx 10^4$  years,  $\lambda\beta \approx 20 \text{ pc}$ . If  $\beta = 0.15$  ( $\epsilon = 10 \text{ MeV/nucleon}$ ),  $\lambda \approx 130 \text{ pc}$ . This value is quite large but not inconsistent with recent ideas on cosmic ray propagation (Ramaty and Lingenfelter, 1971). In particular, if cosmic rays propagate by compound diffusion (Lingenfelter, Ramaty and Fisk, 1971) or if cosmic rays are confined to the galactic disk by reflecting boundaries, both the low anisotropy and abundances of fragmentation products of galactic cosmic rays are not inconsistent with the long diffusion mean free path required for the ionization of the Gum Nebula. Finally, a relatively scatter-free motion in the nebula is also supported by the low values of both the ambient gas density and magnetic field in this region of interstellar space.

The ionization loss rate and the time for the deposition of half the energy of a nonrelativistic particle of mass number  $A$  and nuclear charge  $Ze$  in neutral hydrogen of density  $n_H$  are given by

$$\frac{d\epsilon}{dt} \approx 1.46 \times 10^{-12} Z_{eff}^2 / A n_H \epsilon^{-0.3} \text{ MeV/nuc. sec}^{-1} \quad (3)$$

and

$$t_{1/2} \approx 10^4 \epsilon^{1.3} A / (Z_{eff}^2 n_H) \text{ years} \quad (4)$$

where  $\epsilon$  and  $n_H$  are in MeV/nucleon and  $\text{cm}^{-3}$ , respectively. As a result of electron capture during the slowing down process the effective charge  $Z_{eff}$  becomes smaller than the nuclear charge  $Z$ .  $Z_{eff}/Z$  may be approximated by (Pierce and Blann, 1968)

$$Z_{eff} / Z \approx 1 - \exp(-130 \beta / Z^{2/3}) \quad (5)$$

Since even for  $\text{Fe}^{56}$  at 10 MeV/nucleon  $Z_{eff}/Z \approx 0.9$ , we shall use  $Z$  instead of  $Z_{eff}$  in the evaluation of equations (3) and (4).

In Table 1,  $n_H t_{1/2}$  is given for various 10 MeV/nucleon particles. As can be seen, in  $10^4$  years these particles will deposit a major fraction of their energy only if  $n_H \gg 1 \text{ cm}^{-3}$ . The average electron density  $\langle n_e \rangle$  in the Gum Nebula is only  $0.16 \text{ cm}^{-3}$ , but the density in filaments is much higher,  $n_e \approx X \langle n_e \rangle$  where  $X \approx 65$  is the clumping factor in the nebula (Brandt et al., 1971). A possible model, therefore, is one in which initially the nebular region consisted of neutral clouds or clumps with hydrogen densities approximately equal to the presently observed electron densities in filaments. The particles ejected from the supernova propagate in a scatter-free manner in the intercloud medium and subsequently penetrate clouds and lose their

energy in a time scale shorter than the trapping time in the cloud. A possible trapping mechanisms, based on wave-particle interactions, has been discussed by Ramaty et al. (1971).

If the initial hydrogen density in clouds is equal to the present electron density of about  $10 \text{ cm}^{-3}$ , it is very unlikely that low energy protons have ionized the Gum Nebula, since, as can be seen from Table 1, it would take about  $2 \times 10^4$  years for these particles to lose half their energy. On the other hand, if the ionization were produced by heavy nuclei such as Si and Fe, these particles would deposit sizable fractions of their energy in clouds on a time scale of 2000 to 3000 years leaving about 7000 to 8000 years for scatter-free propagation in the intercloud medium. This is consistent with the estimates of the transit times to the edges of the nebula given above.

A specific consequence of this model is that the degree of ionization of the intercloud medium is much smaller than that of the filaments. This is not the case for models in which the ionization is produced by photons since these lead to the complete ionization of both the clouds and intercloud medium out to an appropriate Strömgren radius.

#### Mass and Energy Requirements of Supernova Ejecta

A fast particle of energy  $\gtrsim 0.1 \text{ MeV/nucleon}$  expends some 36 eV to produce an ion pair (Bethe and Ashkin, 1953). Therefore, if the nebula contains  $N_e \approx 2 \times 10^{62}$  electrons, as suggested by Brandt et al. (1971), the particles ejected by the supernova must lose at least  $1.2 \times 10^{52}$  ergs. For the present value of  $N_e$  used, this is a lower limit, since a fraction of

the energetic particles may slow down in an ionized medium thereby converting their energy directly to heat, and the total number of electrons produced could be larger than Ne since some recombination in the filaments may have already taken place.

The velocity distribution of the ejected material from a supernova explosion may be approximated by (Colgate and McKee, 1969)

$$v = \begin{cases} v_1 (1-F)^{1/3} & ; 0.75 \geq F \geq F_0 = 3/7 \\ 0.67 v_1 F^{-1/4} & ; F < F_0 \end{cases} \quad (6)$$

where F is the external mass fraction. The corresponding number spectrum of nuclei of mass number A in the nonrelativistic region is given by

$$N(\epsilon) = \frac{6}{7} \frac{M_{ej}(A)}{A m_p} \frac{1}{\epsilon} \begin{cases} (\epsilon/\epsilon_0)^{3/2} & ; \epsilon \leq \epsilon_0 \\ (\epsilon_0/\epsilon)^2 & ; \epsilon > \epsilon_0 \end{cases} \quad (7)$$

Upon integration, the total kinetic energy W of the ejected material is

$$W = \frac{6}{5} \frac{M_{ej}}{m_p} \epsilon_0 \quad (8)$$

where  $m_p$  is the proton mass.

Since  $W \gtrsim 1.2 \times 10^{52}$  ergs, the ejected mass in units of a solar mass and the characteristic ejection energy in MeV/nucleon must obey

$$\frac{M_{ej}}{M_\odot} \epsilon_0 \gtrsim 5 \text{ MeV/nucleon} \quad (9)$$

As discussed above,  $\epsilon_0$  cannot be smaller than about 5 MeV/nucleon, since otherwise the particles will not reach the edges of the nebula in the available time of about  $10^4$  years. On the other hand,  $\epsilon_0$  cannot be much larger than about 20 MeV/nucleon, since, as can be seen from Table 1 and



equation (4), the ejected nuclei, even if they are all  $\text{Fe}^{56}$ , will not have enough time to deposit their energy in clouds. For the range  $5 < \epsilon_0 < 20$  MeV/nucleon, the lower limits on the ejected mass range between  $0.25 M_\odot$  to  $1 M_\odot$ . For the efficient ionization of the nebula, the ejected material must consist of nuclei heavier than at least  $\text{C}^{12}$ .

We now proceed to examine the observational consequences of the model.

#### Hard Photon Emissions by Energetic Particles in the Nebula

X-ray emission by bremsstrahlung is a necessary consequence of the interaction of fast nuclei with interstellar gas (Boldt and Serlemitsos, 1969). The photon energy spectrum that would result from the particle distribution given in equation (7) is essentially flat with an end point  $h\nu_0$  at  $(m_e/m_p)\epsilon_0$ , where  $m_e$  and  $m_p$  are the electron and proton masses, respectively.

Let  $M/(Am_p)$  nuclei of mass number  $A$  and atomic number  $Z$  be currently trapped in clouds of density  $n_e$ . The average bremsstrahlung volume emissivity in the Gum Nebula (independent of the ionization state of the gas) is given by

$$\eta = \frac{2\alpha}{\pi} Z^2 \sigma_0 m_e c^2 \frac{n_e}{V} \frac{M}{Am_p} \langle c\beta \rangle \quad (10)$$

where  $\sigma_0 = 6.7 \times 10^{-25} \text{ cm}^2$ ,  $\alpha = 1/137$ ,  $V$  is the volume of the Gum Nebula, and  $\langle c\beta \rangle$  is the particle velocity averaged over the energy spectrum of the particles. For  $\langle \beta \rangle = 0.15$ ,  $Z^2/A = 8.7$  (average of  $\text{Si}^{28}$  and  $\text{Fe}^{56}$  in a ratio of 2 to 1),  $n_e = 10 \text{ cm}^{-3}$  and  $V = 1.35 \times 10^{63} \text{ cm}^3$  (Brandt et al., 1971) we get

$$\eta \approx 9 \times 10^{-28} \frac{M}{M_\odot} \text{ ergs cm}^{-3} \text{ sec}^{-1} \quad (11)$$

According to the geometry of the Gum Nebula described by Brandt et al. (1971), we expect it to appear as a disk source of X-rays, extended in galactic longitude ( $\Delta l \approx 90^\circ$ ) and relatively thin in galactic latitude ( $\Delta b \approx 7^\circ$ ). Collecting radiation from an interval of length  $L$  penetrating the nebula, the intensity viewed by a detector of aperture  $(\Delta b)_0 < \Delta b$  would be expressed by

$$dI/dl = (\Delta b)_0 / (4\pi) \eta L \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ rad}^{-1} \quad (12)$$

Using a detector of  $(\Delta b)_0 = 4^\circ$ , viewing at  $l \approx (260 \pm 40)^\circ$ , which spans the Gum Nebula, Cooke, Griffiths and Pounds (1969) observed an enhanced X-ray emission associated with the galactic disk of about  $3 \times 10^{-9} \text{ ergs (cm}^2 \text{ sec rad)}^{-1}$  above 1.4 keV, with an essentially flat energy spectrum extending to about 10 keV. The upper limits to this flux at energies above 12.5 keV, as set by Hudson, Peterson, and Schwartz (1971), provide evidence that the spectrum is characterized by a break in the vicinity of about 10 keV. Using the volume emissivity as obtained from equation (11),  $L = 400 \text{ pc}$  and  $(\Delta b)_0 = 4^\circ$ , we get  $dI/dl = 6 \times 10^{-9} M/M_\odot \text{ ergs sec}^{-1} \text{ cm}^{-2} \text{ rad}^{-1}$ . Since a significant part of the apparently diffuse background observed from the direction of the Gum Nebula may be coming from undetected discrete sources (Cooke and Pounds, 1971), the flux of  $3 \times 10^{-9} \text{ ergs cm}^{-2} \text{ sec}^{-1} \text{ rad}^{-1}$  must be considered as an upper limit. This then sets an upper limit  $M/M_\odot < 0.5$  on the mass of energetic charged particles currently trapped in clouds.

In addition to bremsstrahlung X-rays, contemporary fluxes of energetic heavy nuclei in dense clouds may also produce detectable gamma-ray line emission in the few MeV range. As an example, we consider the 1.78 MeV

line of  $\text{Si}^{28}$ . The cross section  $\sigma_\gamma$  for the reaction  $\text{Si}^{28} (p, p') \text{Si}^{28*1.78 \text{ MeV}}$  has a threshold at about 5 MeV, peaks at about 9 MeV and has a value of about 300 mb at 10 MeV (McGowan et al., 1969, 1970).

As above we assume that  $M/(Am_p)$  particles are currently trapped in clouds. The average volume emissivity of the Gum Nebula in line emission at a photon energy  $E_\gamma$  is then given by

$$\eta(E_\gamma) = \sigma_\gamma E_\gamma (n_p/V) (2M/3Am_p) \langle \epsilon \beta \rangle \quad (13)$$

where  $n_p$  equal to  $n_e$  is the proton density in clouds, and the factor of 2/3 is the assumed fraction of silicon nuclei in the supernova ejecta.

For the values of  $n_p = n_e$ ,  $V$  and  $\langle \epsilon \beta \rangle$  given above

$$\eta(1.78 \text{ MeV}) \simeq 8 \times 10^{-28} \frac{M}{M_\odot} \text{ ergs cm}^{-3} \text{ sec}^{-1} \quad (14)$$

Since present measurements of gamma rays at these energies have been made with omnidirectional detectors only (Vette et al., 1970), we shall make the simplifying assumption that the flux at earth is produced by a point source at the center of the Gum Nebula. The flux seen by an omnidirectional detector will then be given by

$$F(E_\gamma) = \eta(E_\gamma) V / (4\pi r^2 E_\gamma) \quad (15)$$

For  $r \simeq 460$  pc,  $E_\gamma = 1.78$  MeV and  $M/M_\odot < 0.5$ ,  $F(1.78 \text{ MeV}) < 8 \times 10^{-3}$  photons  $\text{cm}^{-2} \text{ sec}^{-1}$ . This flux should be compared with the omnidirectional counting rate of  $1.2 \times 10^{-1}$  photons  $\text{cm}^{-2} \text{ sec}^{-1}$  in the 1 to 2 MeV range (Vette et al., 1970). Since the energy of the photon-emitting nuclei is about 10 MeV/nucleon or less, line broadening should be less than 15%. Therefore, detectable gamma-ray line emission could be observed with detectors of moderate energy resolution.

It is of some interest to speculate about line emission at 4.43 MeV from  $C^{12}$  and 6.14 MeV from  $O^{16}$ . The cross sections for the excitation of these levels were plotted as a function of energy by Lingenfelter and Ramaty (1967). At 10 MeV/nucleon  $\sigma_{\gamma} \approx 200$  mb for  $C^{12}$  and  $\sigma_{\gamma} \approx 100$  mb for  $O^{16}$ . If  $M_C$  and  $M_O$  are the present masses of energetic carbon and oxygen nuclei in clouds the expected photon fluxes from the Gum Nebula are  $F(4.43 \text{ MeV}) \approx 4 \times 10^{-2} M_C/M_{\odot} \text{ photons cm}^{-1} \text{ sec}^{-1}$  and  $F(6.14 \text{ MeV}) \approx 1.5 \times 10^{-2} M_O/M_{\odot} \text{ photons cm}^{-2} \text{ sec}^{-1}$ . When compared with the observed counting rate of about  $5.6 \times 10^{-2} \text{ photons cm}^{-2} \text{ sec}^{-1}$  in the 4 to 6 MeV band (Vette et al., 1970), we see that line emission from carbon and oxygen could be detected and, moreover, it could account for at least part of the excess radiation above the intergalactic background as calculated by Brecher and Morrison (1969).

In addition to the gamma ray region, line emission should also be produced in the X-ray region as a result of charge exchange between energetic nuclei and H atoms resulting in the capture of electrons to excited states. Cascades down to the ground state occur, which produce the analogue of  $Ly\alpha$  and  $Ly\beta$  emission for the case of capture of K-electrons. Silk and Steigman (1969) have given a discussion of this process, with application to low energy galactic cosmic rays. The contemporary flux of X-ray line emission, however, is difficult to determine, since unlike bremsstrahlung and nuclear collision which do not depend on the ionization state of the ambient matter, charge exchange takes place in neutral hydrogen only. Estimates of the time integrated fluxes in the 7 keV line of iron and 2 keV line of silicon were given by Ramaty et al. (1971).

### Cooling of the Nebula

Alexander et al. (1971) suggested that the temperature of the nebula as a whole is quite high, probably in excess of  $5 \times 10^4 \text{K}$ . While it is possible that the dense filaments could at present be cooler than  $10^4 \text{K}$ , it is of some interest to examine the effects of a contemporary source of ionization and heating on the thermal state of the filaments.

According to Cox and Tucker (1969), for a gas of cosmic abundances in ionization equilibrium, the radiative loss rate at  $5 \times 10^4 \text{K}$  is  $P \approx 2 \times 10^{-22} n_e^2 \text{ergs cm}^{-3} \text{sec}^{-1}$ . The corresponding cooling time is  $t_c \approx 3/2 n_e kT/P \approx 1700/n_e$  years. For  $n_e = 10 \text{ cm}^{-3}$ ,  $t_c \approx 170$  years, much shorter than the age of the nebula.

The rapid cooling of the filaments can be partially compensated by a contemporary source of heat such as a large flux of energetic particles presently trapped in clouds. The rate of energy loss of a particle of mass number  $A$  and nuclear charge  $Ze$  in a plasma of density  $n_e$  is approximately given by equation (3) with  $n_H$  replaced by  $4n_e$  (Hayakawa and Kitao, 1956). If  $M/(A m_p)$  nuclei are currently trapped in clouds, the contemporary heat input is given by

$$Q \approx 5.6 \times 10^{-22} (Z^2/A) \epsilon^{-0.3} n_e \frac{M}{M_\odot} \text{ergs cm}^{-3} \text{sec}^{-1} \quad (16)$$

For  $Z^2/A = 8.7$ ,  $\epsilon = 10 \text{ MeV/nucleon}$ ,  $n_e = 10 \text{ cm}^{-3}$  and  $M/M_\odot < 0.5$ ,  $Q < 0.6P$ . Thus, even though a contemporary flux of energetic particles, equal to the upper limit determined from the calculated bremsstrahlung emission and the observed disk component of diffuse x-rays could make a contribution to the

maintenance of the temperature in the filaments, it is not quite sufficient to balance the radiative energy loss of the plasma. The characteristic time scale for contemporary heating,  $t_h$ , is given by equation (4) with  $n_H$  replaced by  $4n_e$ . For  $Z^2/A = 8.7$ ,  $\epsilon = 10$  MeV/nucleon and  $n_e = 10 \text{ cm}^{-3}$ ,  $t_h \approx 800$  years.

The radiation loss  $P$ , however, could be smaller than the value calculated by Cox and Tucker (1969) if the abundances of carbon and oxygen in the Gum Nebula are below universal abundances or if the ions  $C^{+1}$  to  $C^{+3}$  and  $O^{+1}$  to  $O^{+5}$  are significantly depleted from their values corresponding to ionization equilibrium by the initial ionization process. If the maintenance of a high temperature in the filaments is achieved by the latter mechanism, the characteristic time of interest is the recombination time of  $O^{+6}$  to  $O^{+5}$  and  $C^{+4}$  to  $C^{+3}$ .

Up to temperatures of a few times  $10^5 \text{ K}$  dielectronic recombination for  $O^{+6}$  and  $C^{+4}$  is negligible. Using Seaton's (1959) hydrogenic approximation, the radiative recombination coefficient to all levels of an ion  $X^{+m}$  is given by (e.g. Allen and Dupree, 1969)

$$\alpha \approx 2 \times 10^{-11} (m+1)^2 T^{-\frac{1}{2}} \left( 0.43 + \frac{1}{2} \ln \lambda + \frac{0.47}{\lambda^{1/3}} \right) \text{cm}^3 \text{sec}^{-1} \quad (17)$$

where  $\lambda = 157890 (m_H)^2 / T$ . For  $n_e = 10$  and  $T = 2 \times 10^5 \text{ K}$ , the recombination time for both  $O^{+6} \rightarrow O^{+5}$  and  $C^{+4} \rightarrow C^{+3}$  is about 900 years. By combining this time scale with the contemporary heating time  $t_h$ , we see that the onset of rapid cooling could be delayed by as much as 1500 to 2000 years. A high temperature in the filaments could then be consistent with a delayed mechanism for the ionization and heating of the Gum Nebula.

# Ionization and Heating of the Interstellar Medium

Several recent theoretical descriptions (Pikel'ner 1967; Balasubrahmanyam et al. 1968; Spitzer and Tomasko 1968; Spitzer and Scott 1969; Goldsmith, Habing, and Field 1969) of ionization and thermal equilibria for interstellar HI regions, based upon current models for the interstellar gas, indicate that the rate of ionization per hydrogen atom is  $\zeta \approx 10^{-15}$  (sec H atom) $^{-1}$ . Hjellming, Gordon, and Gordon (1969) find that observed pulsar dispersion measures may be best fitted with such a model for  $\zeta = (2.5 \pm 0.5) \times 10^{-15}$  (sec H/atom) $^{-1}$ . For an equilibrium situation, the rate of electron-ion recombination is the most direct measure of  $\zeta$ ; recent observations of H $\beta$  hydrogen line emission from interstellar HI (Reynolds 1971) yield a direct measure of the recombination rate, and the corresponding ionization rate in the regions examined could be as high as  $10^{-14}$  (sec H atom) $^{-1}$ .

Since essentially all the gas in the Gum Nebula has been ionized by the supernova explosion, the average rate of ionization in interstellar hydrogen by such events would be given by

$$\zeta < n_H > = f_{SN} N_e \quad (18)$$

where  $< n_H >$  is the mean interstellar hydrogen density and  $f_{SN}$  is the average supernova frequency per unit volume in the galaxy. If supernova occur at a rate of 1 per 100 years in a volume of  $4 \times 10^{66}$  cm $^3$ ,  $f_{SN} \approx 8 \times 10^{-77}$  cm $^{-3}$ sec $^{-1}$ . For  $N_e \approx 2 \times 10^{62}$  electrons (Brandt et al. 1971), we obtain  $\zeta < n_H > \approx 1.6 \times 10^{-14}$  sec $^{-1}$ cm $^{-3}$ . Radio observations at 21 cm indicate a mean value for the neutral hydrogen density in the galactic plane of about 0.7 cm $^{-3}$  (Spitzer 1968); however, optical depth effects probably



raise  $\langle n_H \rangle$  to  $\sim 1 \text{ cm}^{-3}$ . A further increase by about a factor of 2 in the value of  $\langle n_H \rangle$  may be due to the presence of molecular hydrogen in dense clouds. Hence the mean galactic value of  $\xi$  as indicated by the parameters deduced for the Vela X supernova is about  $8 \times 10^{-15} \text{ sec}^{-1} (\text{H atom})^{-1}$ . This ionization rate could be reduced if the frequency of supernova explosions of the type that produced the Gum Nebula is lower than the assumed rate of 1 per 100 years or if the actual free electron content of the Gum Nebula is less than that estimated by Brandt et al. (1971). Furthermore, even if the average supernova output is similar to that of Vela X but occurs in a region with larger magnetic fields, so that the particles propagate over a shorter distance before they lose their energy, the ionized volume produced by the supernova would be smaller than that of the Gum Nebula. In this case, the total ionization per supernova would be reduced since a larger fraction of the total energy would go into heating. Also, those supernovae which occur at more than about 100 pc away from the galactic plane (e.g. the Crab) will produce energetic particles which may escape from the disk without producing significant ionization.

In order for HII regions such as the Gum Nebula to merge into the HI of the interstellar medium, the recombination and cooling times of the clouds should be much less than the time between supernova explosions  $t_{\text{SN}}$  in the volume of the nebula. For  $f_{\text{SN}} = 8 \times 10^{-77} \text{ cm}^{-3} \text{ sec}^{-1}$  and  $V = 1.35 \times 10^{63} \text{ cm}^3$ ,  $t_{\text{SN}} \approx 3 \times 10^5$  years.

The recombination time of hydrogen is approximately  $t_{\text{rec}} \approx 130 T^{0.7}/n_e$  (Bates and Dalgarno 1962). For  $n_e = 10 \text{ cm}^{-3}$  and  $T = 5 \times 10^4 \text{ K}$ ,  $t_{\text{rec}} \approx 2.5 \times 10^4$  years. Since the recombination rate increases with decreasing temperature,



both  $t_c$  and  $t_{rec}$  are much smaller than  $t_{SN}$ , so that the ionized clouds in the Gum Nebula will rapidly merge into the HI of the interstellar medium.

In the intercloud medium, for a density  $\langle n_e \rangle \approx 0.16 \text{ cm}^{-3}$ , the temperature will not decrease appreciably below  $10^4 \text{ K}$  in  $3 \times 10^5$  years. The recombination time then becomes comparable to  $t_{SN}$  so that the degree of ionization is approximately constant as a function of time. The fact that the inferred degree of ionization of the intercloud medium probably does not exceed about 10% (Hjellming, Gordon and Gordon, 1969) is consistent with a cosmic-ray model for the ionization of the Gum Nebula, since, as discussed above, the energetic charged particles from the supernova will deposit most of their energy in clouds and not in the intercloud medium.

## REFERENCES

- Alexander, J.K., Brandt, J.C., Maran, S.P., and Stecher, T.P., 1971,  
Ap. J., in press.
- Allen, J.W., and Dupree, A.K., 1969, Ap. J. 155, 27.
- Balasubrahmanyam, V.K., Boldt, E.A., Palmeira, R.A.R., and Sandri, G.,  
1968, Can. J. Phys. 46, S633.
- Bates, D.R., and Dalgarno, A., 1962, Atomic and Molecular Processes,  
D.R. Bates, Editor, Academic Press, New York.
- Bethe, H.A., and Ashkin, J., 1953, Experimental Nuclear Physics, Vol. 1,  
E. Segre, Editor, John Wiley & Sons, Inc., New York, p. 166.
- Boldt, E., and Serlemitsos, P., 1969, Ap. J. 157, 557.
- Brandt, J.C., Stecher, T.P., Crawford, D.L., and Maran, S.P., 1971,  
Ap. J. (Letters) 163, L99.
- Colgate, S.A., and McKee, G., 1969, Ap. J. 157, 623.
- Cooke, B.A., Griffiths, R.E., and Pounds, R.A., 1969, Nature 224, 134.
- Cox, D.P., and Tucker, W.H., 1969, Ap. J. 157, 1157.
- Goldsmith, D.W., Habing, H.J., and Field, G.B., 1969, Ap. J. 158, 173.
- Hayakawa, S., and Kitao, K., 1956, Prog. Theor. Phys. 16, 139.
- Hjellming, R.M., Gordon, C.P., and Gordon, K.J., 1969, Astron. Astrophys.  
2, 202.
- Hudson, H.S., Peterson, L.E., and Schwartz, D.A., 1971, Nature 230, 177.
- Lingenfelter, R.E., and Ramaty, R., 1967, High-Energy Nuclear Reactions  
in Astrophysics, B.S.P. Shen, Editor, W.A. Benjamin, New York.

Lingenfelter, R.E., Ramaty, R., and Fisk, L.A., 1971, *Astrophys. Letters*, 8, 93.

McGowan, F.K., Milner, W.Y., Kim, H.J., and Hyatt, W., 1969, *Nuclear Data Tables*, A6, 353.

McGowan, F.K., Milner, W.T., Kim, H.J., and Hyatt, W., 1970, *Nuclear Data Tables*, A8, 199.

Pierce, T.E., and Blann, M., 1968, *Phys. Rev.* 173, 390.

Pikel'ner, S.B., 1967, *Astrophys. Letters* 1, 43.

Ramaty, R., Boldt, E.A., Colgate, S.A., and Silk, J., 1971, *Ap. J.*, in press.

Ramaty, R., and Lingenfelter, R.E., 1971, *Proc. of the Lyngby Meeting on the Isotopic Composition of Cosmic Ray Nuclei*, to be published, GSFC preprint X-660-71-221.

Reichley, P.E., Downs, G.S., and Morris, G.A., 1970, *Ap. J. Letters*, 159, L35.

Reynolds, R., 1971, Ph.D. Thesis, University of Wisconsin.

Seaton, M.J., 1959, *M.N.R.A.S.*, 119, 81.

Shklovsky, I.S., 1970, *Nature* 225, 252.

Silk, J., and Steigman, G., 1969, *Phys. Rev. Letters* 23, 597.

Spitzer, L., Jr., 1968, *Diffuse Matter in Space* (New York: Interscience).

Spitzer, L., and Scott, E.H., 1969, *Ap. J.* 158, 161.

Spitzer, L., and Tomasco, M.G., 1968, *Ap. J.* 152, 971.

TABLE 1

	$n_H t_{1/2} (\text{cm}^{-3} \text{ years})$
$\text{H}^1$	200000
$\text{C}^{12}$	67000
$\text{Si}^{28}$	29000
$\text{Fe}^{56}$	16000